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Mesosystem Weather in the Pacific Northwest A Summer Case Study

OWEN P. CRAMER[1]—*Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, Calif.*

ABSTRACT—Three kinds of mesosystems—two squall mesosystems, an instability line, and a strong marine push—were all observed in Oregon on the same day. Each system produced sudden changes in temperature and gale-force winds, yet none was identified on routine synoptic analyses. The development and progress of each mesosystem is reconstructed in a series of detailed sea-level analyses. Effects on local winds and temperature of a pseudo cold front associated with a squall mesosystem in mountainous terrain were documented as the system passed through a mesonet in the Cascade Range. The impact of these mesosystems emphasizes the need for greater attention to mesoscale systems for identification and warning of important summer weather events. The mesosystems appear to be closely related to the approach of a minor short-wave trough, with maximum development at the 250-mb level.

1. INTRODUCTION

Usual weather analyses, prepared in deadline-demanding haste at the synoptic scale, may smooth over small-scale, pressure-pattern features associated with important weather phenomena. Intensive analysis of an unusually windy thunderstorm episode in the Pacific Northwest revealed mesopatterns that were not apparent from routine analysis.

Summer weather in the Pacific Northwest is predominantly fair with only a few rainy periods of 1–3 days. Most changes are gradual. Fronts from storms in the westerlies cross the area only rarely, usually as dissipating remnants. But the physiography of the region, the prevailing circulation that occasionally pumps in unstable marine air at high levels, and contrasting cool marine and warm continental air masses at lower levels may combine to produce mesoscale weather events characterized by sudden changes. Three types of mesoevents were observed the afternoon of Sept. 9, 1963—a major marine push, two squall mesosystems (Fujita 1963), and an instability line (Fulks 1951). Thirty-knot winds and temperature drops of 15° F or more with the marine push and sudden 40-kt winds and thunderstorms with at least one squall mesosystem were notable in that summer's most important weather events.

By themselves, the abrupt marine push with its winds and the instability line with wind and thunderstorms would have been considered quite important fire-weather events. They were additionally important on Sept. 9, 1963, in apparently providing the trigger action that set up the second squall mesosystem. Synoptically, all these mesoevents were related to the approach of a minor, short-wave upper trough from the south.

[1] The author is currently stationed at Portland, Oreg.

Although the Pacific Northwest is not usually considered an important severe storm area, fire control specialists concerned with lightning fires know that thunderstorms occur on an average of 20 days in the summer alone in the mountain areas of northern Washington and eastern Oregon (Cramer 1965). Occasional typical microbarograms from National Weather Service stations and cooperative observer reports of wind and hail damage during periods of thunderstorm activity indicate that significant squall mesosystems have occurred here. Squall mesosystems usually go unreported because the network of stations is sparse in the areas of greatest thunderstorm frequency. The second of the two squall mesosystems of September 9 began over western Oregon, where its progress could be traced. This storm started some 200 forest fires in Oregon and Washington and produced gale-force winds over a quarter of the two-State region. Although not a rain producer itself, this mesosystem had fortunately been preceded by damp weather, or its lightning and winds might have led to a forest fire disaster. A somewhat similar complex of thunderstorms started 369 fires in northeast Oregon on the night of July 19, 1960. Those fires burned 64,500 acres of forest land and cost $6.7 million in suppression and damage.

Fujita (1963) has described the typical squall mesosystem in considerable detail. It has several characteristics not seen in the usual individual thunderstorm:

1. The squall mesosystem has a pronounced and distinctive effect on the air pressure pattern in five defined stages including formation and dissipation of a meso-High and a meso-Low.

2. The system is generally oval and is rimmed by a pseudo cold front that may expand to an area that is an order of magnitude greater than an individual thunderstorm.

3. The mesosystem has a longer life span, beginning with the parent thunderstorm and ending several hours later, but generally less than 24 hr later.

4. Multiple thunderstorms usually occur along the pseudo cold front, which is characterized by strong winds, a pressure rise, and a distinct temperature drop as the meso-High expands and advances.

A squall mesosystem is considerably different from the average Pacific Northwest summer thunderstorm as determined by Morris (1934). He examined "more than 6,000 systematic reports describing 2,600 lightning storms seen by U.S. Forest Service fire lookouts in Oregon and Washington during the summer months" of 7 consecutive summers. He found the average storm track to be 25–35 mi long and 5 mi wide; over this track, the storm moved at an average speed of 8–15 kt from some southerly direction during approximately a 2-hr period. By comparison, the second squall mesosystem described in this paper was readily identifiable as it moved over 260 mi at an average speed of 33 kt during a 6-hr period with a pronounced discontinuity zone extending over 300 mi.

2. SYNOPTIC SITUATION

On September 9, the usual summer continental anticyclone dominated the upper air pattern over the western part of the country and northern Mexico. This High and the broad semipermanent trough offshore produced a flow of tropical maritime air from the south over the west coast (figs. 1A–1F). Branches of the main jet stream, the closest at 200 mb, were over northern Mexico and the Arctic. A diffuse, cool, high-level Low, embedded in the major trough since September 1, had been migrating gradually northward off the California coast. On the morning of Sepember 9, a minor short-wave trough aloft extended eastward from the shrinking Low across California near the latitude of San Francisco. This trough was accompanied and followed by stronger winds at the 700- and 500-mb levels, with jet-force winds around 300 mb. The trough axis had progressed only to northern California by 1600 PST (figs. 1D–1F), by which time all mesosystems were active some 250 mi to the north in Oregon. These systems developed in the area of positive vorticity advection and difluence north of the strongest winds (fig. 1D). Twelve hr later, when all mesosystems had dissipated, the minor trough lay midway across Oregon (figs. 1G–1I). By that time, substantial height falls at all surfaces and large temperature drops below 350 mb accompanied sharpening of the trough.

At sea level, the 0400 PST analysis on the 9th (fig. 2) showed a heat trough extending northward from the California heat Low between the Coast and the Cascade Mountain Ranges. This is a typical pattern for hot weather west of the Cascades. The maritime tropical air mass aloft that had already produced widespread cumulonimbus clouds and a few 100°F readings over western Oregon on the 8th persisted on the 9th for the third successive 90°F-plus day. In northern California, midday temperatures were running lower in brisk southerly winds.

The approach on September 9 of a weak upper Low from off the California coast was a synoptic pattern recognized as a thunderstorm producer in western Oregon, but it has not heretofore been linked with the extreme weather reported here. A similar situation, complete with exten-

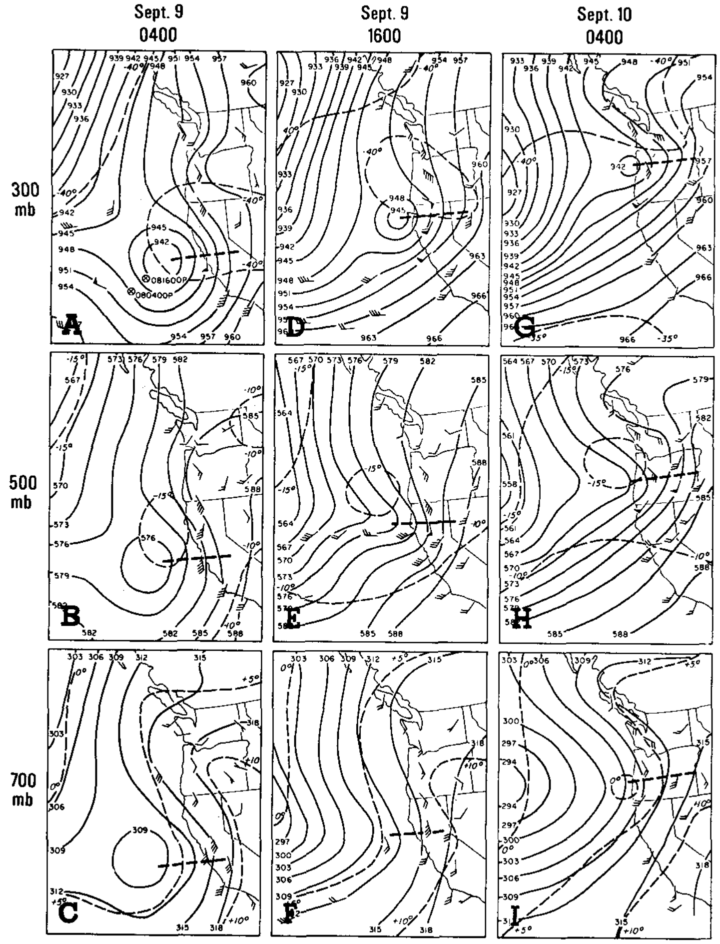

FIGURE 1.—Upper air charts for 0400 and 1600 PST, Sept. 9 and 0400 PST, Sept. 10, 1963.

sive thunderstorms and a squall line, occurred on Sept. 22, 1966, but the Low aloft remained off the northern California coast and there was no marine push. More recently, extensive thunderstorms over the entire northwest and a marine push west of the Cascades accompanied an almost identical sequence Aug. 30, 1970, but no squall line developed. A careful review would undoubtedly turn up additional examples.

3. THE MARINE PUSH

Of the mesoevents that occurred on September 9, the first noted in the Willamette Valley was the reinforced sea-breeze front or marine push. It was unusually vigorous at some stations, producing sharp temperature drops, a wind shift, and a sustained increase in wind speed.

As used in the Pacific Northwest, the term *marine push* refers to an abrupt transition from domination by warm continental air to cool marine air. It exceeds the diurnal sea breeze in vigor, depth, and duration. It may occur at any time of day, with considerable wind in late afternoon and evening, or with little surface indication at valley stations in early morning hours. The marine push results from a shift of warmest air aloft (850- to 700-mb levels) from over or near the coast to farther inland. This produces an inland shift in the sea-level heat trough and the influx of cool marine air on its west side. When the marine

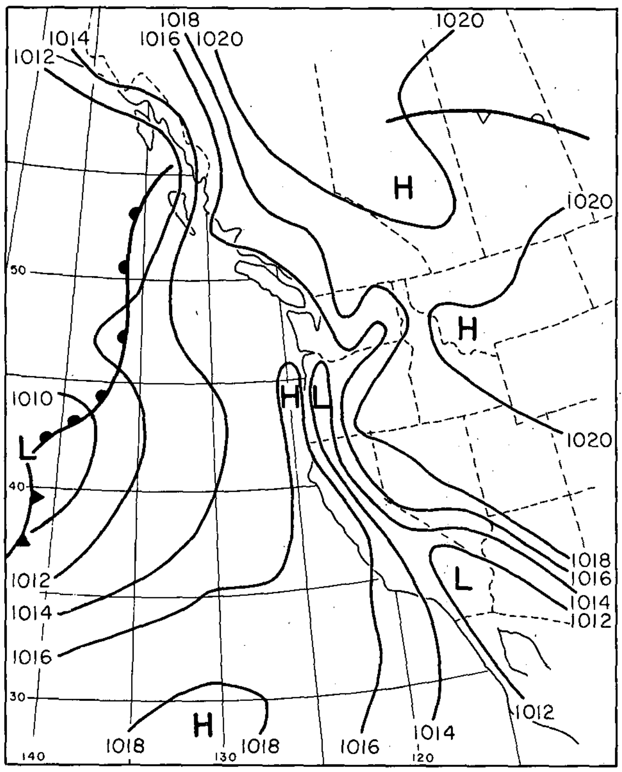

FIGURE 2.—Sea-level map for 0400 PST, Sept. 9, 1963.

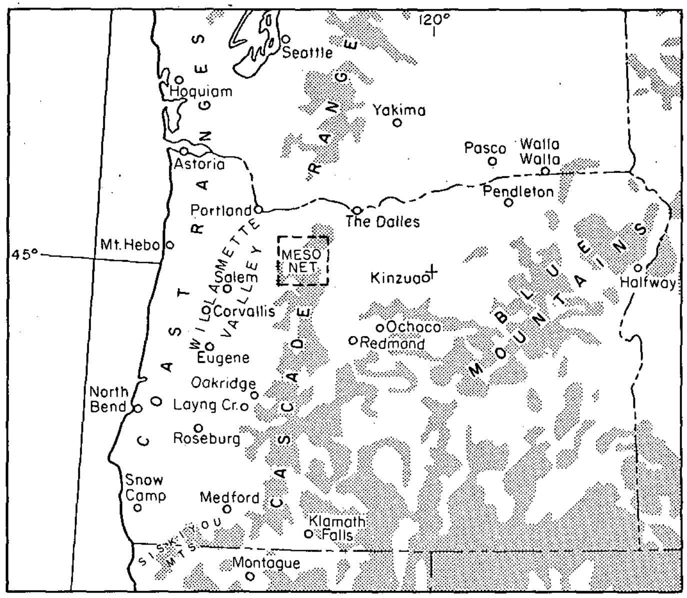

FIGURE 3.—Study area, Pacific Northwest. Shaded area is above 5,000 ft MSL.

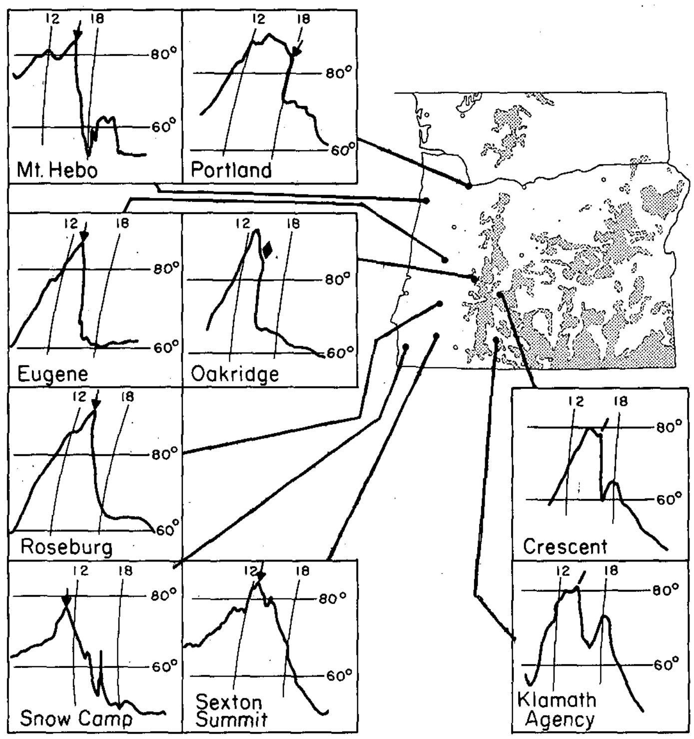

FIGURE 4.—Thermograms showing passage of marine-push front (↓), instability line at Klamath Falls and Crescent (/), and pseudo cold front associated with a squall mesosystem at Oakridge (♦).

push occurs after a hot day, and it usually does, it may produce a marked change of air in at least the lower 5,000 ft from hot dry to cool stratus. Maximum temperatures are considerably lower for at least a day. The change may be triggered by an approaching minor short-wave trough. Precipitation is usually limited to possible drizzle from stratus. Hot spells west of the Cascades are often terminated by such a marine push (e.g., Cramer and Lynott 1970).

Temperatures along the coast had been low on September 8 but were in the 90s a few miles inland. On the 9th, coastal air remained cool because the early morning east-to-southeasterly winds across the Cascades did not reach the coast. The pressure gradient from the coast to the Willamette Valley was about 2 mb greater than on the 8th. Along the coast, a sea breeze began by 0900 PST at Astoria, Oreg., 1100 at Hoquiam, Wash., and noon at North Bend, Oreg. (fig. 3). Remote stations in the Siskiyou Mountains of southwest Oregon reported suddenly dropping temperatures in the late morning and early afternoon. The hygrothermograph at Snow Camp Lookout, Oreg. (elevation 4,223 ft), showed a drop from 76°F near 1100 PST with a light east wind to 53°F with fog and a 15-kt west wind at 1500 PST (fig. 4). At 1500 PST, a similar temperature drop occurred at Mount Hebo (elevation 3,154 ft) in the northern Oregon Coast Range. There, the temperature dipped from 84° to 51°F in less than 3 hr. Considerably deeper than the diurnal sea breeze, this invasion of cool ocean air was a typical marine push.

The cooler air moved across the Coast Range rather slowly in most places. A light west wind reached Corvallis, Oreg., at 1200 PST, interrupting the diurnal increase in temperature at 82°F. Forecasters have found that, at the breakup of a hot spell, the cool marine air reaches Corvallis well ahead of other reporting stations in the Willamette Valley because Corvallis is on the west side of the valley and the terrain in the Coast Range to the west is comparatively low. Similarly, the temperature rise was interrupted at approximately 1330 PST at 88°F

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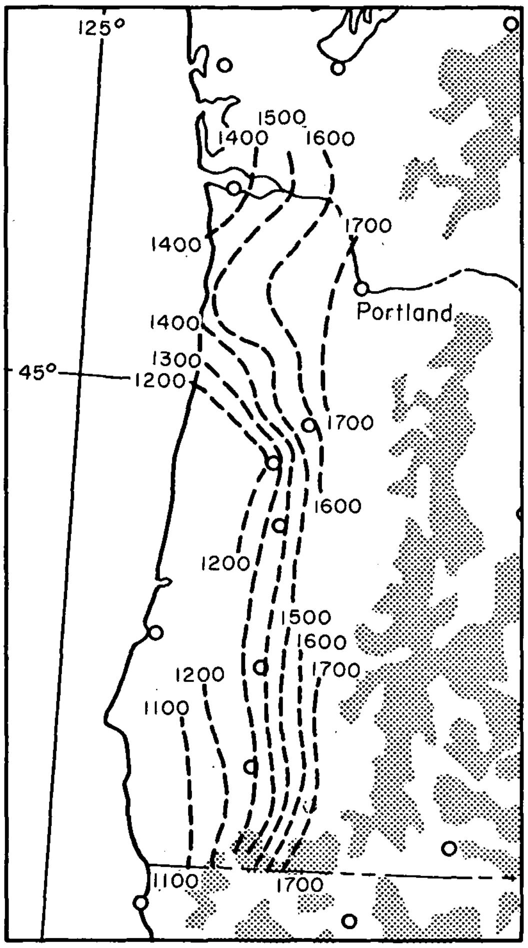

FIGURE 5.—Isochrone analysis of the marine-push front.

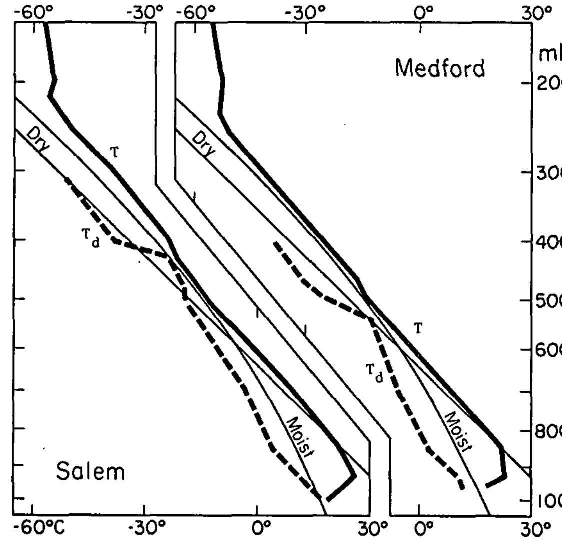

FIGURE 6.—Salem and Medford, Oreg., raobs for 0400 PST, Sept. 9, 1963.

at Eugene, Oreg., and at approximately 1345 PST at 93°F at Roseburg, Oreg. Although the passage of the marine-push front was accompanied by a wind shift and a temperature drop, it had little effect on air pressure as indicated on barograms. At Eugene and Roseburg, for example, the pressure continued to fall for 1–2 hr after the temperature started to drop. This would imply a rather shallow layer of cool air at those stations at that time.

Progress of the marine-push front is shown in figure 5. In the Willamette Valley, this front separated air masses of considerable contrast—at 1500 PST, Corvallis reported 70°F and 24-kt west winds, while Salem, 29 mi northeast, had 94°F and 10-kt north-northeast winds. An hour later, Corvallis reported 65°F with 29-kt west winds gusting to 38 kt.

4. THE FIRST SQUALL MESOSYSTEM

The air mass over both eastern and western Oregon favored thunderstorm development. The 0400 PST radiosonde observations at Salem and Medford, Oreg. (fig. 6), had shown instability—Showalter indexes of 0 at Salem and −1 at Medford. These values have been found by fire-weather forecasters to indicate a high probability of thunderstorms in this mountainous region. Soundings of this type (i.e., comparatively dry at low levels and moist at high levels) have been associated with intense tornado-producing thunderstorms during the summer months over the western and Northern Plains States (Beebe 1955). This is in direct contrast, however, to the generally recognized classic sounding for severe convective activity in the Central Plains, which shows low-level moisture and dryness aloft. Instability had been visually confirmed by the appearance of altocumulus castellanus clouds over many Oregon weather stations by late morning. At 1300 PST (fig. 7A), cumulonimbus were reported over southern Oregon, northern California, and in the Blue Mountains of northeast Oregon. A thunderstorm was in progress at Redmond, Oreg., and another was probably responsible for a sudden drop in temperature at Layng Creek and Oakridge Ranger Stations southeast of Eugene (fig. 3). This was the environment in which the first squall mesosystem formed.

Earliest indication of mesosystem development was an abrupt drop in temperature at Ochoco Ranger Station in central Oregon about 1100 PST (fig. 8), presumably from a thunderstorm. That station remained in cool air for 4½ hr. Some 45 mi northeast and 2 hr later, cool air arrived abruptly at Kinzua, where, following a 16°F drop, cool air was present for the rest of the day. Another 40 mi east, and 1/2 hr later, the temperature at Ukiah dropped from 96° to 66°F in less than 2 hr and remained low until the next day. Fujita (1959) described this type of mesosystem as a "dome-type pressure disturbance" that forms with thunderstorm activity "and grows into a mesoscale system . . . in several hours."

The impact of this system was not fully documented until it reached Pendleton (PDT), Oreg., about 1525 PST with a wind shift from NNE at 11 kt to SSW at 22 kt, gusts to 30 kt, blowing dust, a 12°F temperature drop, 2.4-mb rise in pressure (fig. 9), and cumulonimbus in all quadrants (fig. 7B). Similar changes occurred when the system's pseudo cold front reached Walla Walla and Pasco, Wash. The retreating edge of the meso-High

FIGURE 7.—Selected regional sea-level pressure analyses for Sept. 9, 1963, showing development of mesosystems.

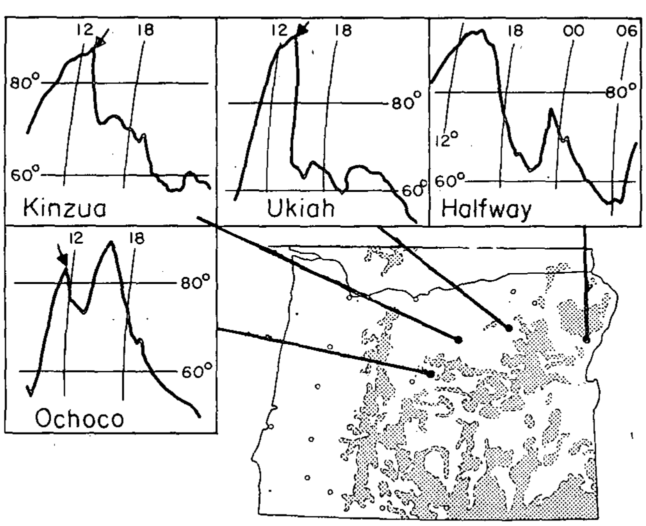

FIGURE 8.—Thermograms showing passage of pseudo cold front in northeast Oregon.

passed Pendleton, Oreg., abruptly at 1730 PST with a 2.7-mb drop and a slackening of wind. This abrupt pressure drop is characteristic of the mesodepression that begins to form behind the meso-High in the mature stage of a squall mesosystem (Fujita 1963, Williams 1953).

5. INSTABILITY LINE

At about the same time that the squall mesosystem was developing in central Oregon, other changes were occurring farther south. Between noon and 1300 PST, the wind at Montague, Calif., changed from calm to south at 25 kt with gusts to 32 kt, and the temperature began a gradual drop from near 90°F (fig. 7A). At 1400 PST, a thunderstorm was reported at Kingsley AFB, Klamath Falls, Oreg., with a 1.3-mb pressure rise, a 20°F temperature drop, and cumulonimbus, lightning, and thunder reported in all quadrants.

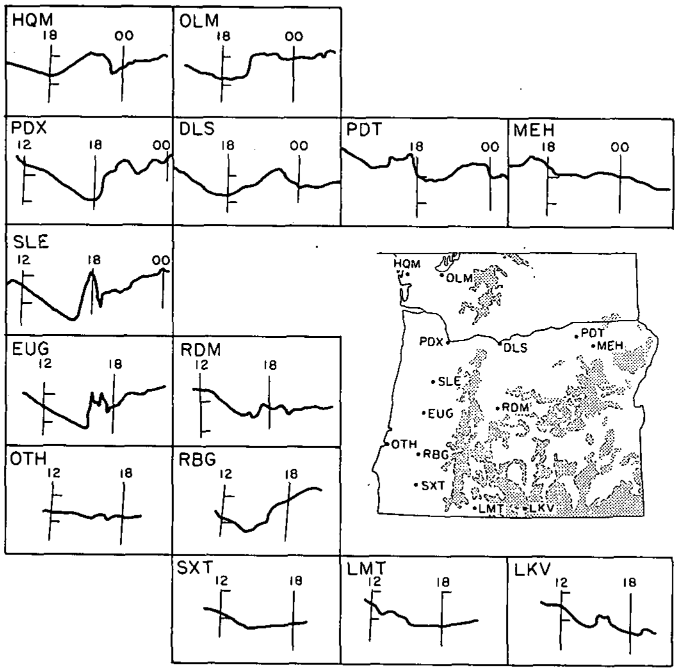

FIGURE 9.—Barograms for squall mesosystems. Vertical graduations are 0.1 in. of mercury.

Also at 1400 PST, a thunderstorm precipitation cell 15 mi across was observed by aircraft radar 20 mi northeast of Medford. From that time on, a regular progression of events marked the advance of an intensifying impulse line or instability line (Fulks 1951) marked by thunderstorms, pressure rises, and characteristic wind shifts that could be followed across Oregon and into Washington for the ensuing 8 hr. Perhaps the line might be called the first stage of squall mesosystem development, but the typical squall mesosystem pattern was not evident until later.

6. THE SECOND SQUALL MESOSYSTEM

The instability line reached Eugene (EUG), Oreg., at approximately 1530 PST accompanied by a thunderstorm and a pressure rise of 4 mb indicating the formation of a meso-High (fig. 9). Already in the cool air behind the marine-push front that had passed more than 1 hr earlier, Eugene showed no significant change in temperature or wind attributable to the thunderstorm and accompanying pseudo cold front, which apparently remained aloft.

The appearance of a definite meso-High at Eugene (fig. 7B) indicated the *initial stage* of a squall mesosystem. This meso-High expanded in all directions, reaching Salem (SLE) on the north and Roseburg (RBG) on the south by 1700 PST (fig. 7C). The marine-push front had brought cooler air to Roseburg 2 hr earlier, so that the southern edge of the meso-High produced no marked changes there except in pressure (fig. 9).

At Salem, although the marine-push front had passed an hour earlier and had produced a wind shift from NNE at 10 kt to NW at 13 kt, the pseudo cold front of the squall mesosystem dropped the temperature from 92°F at 1600 PST to 74°F an hour later. With the passage of the pseudo cold front, the wind shifted to SW at 18 kt with gusts to 30 kt. Subsequent passages followed this pattern. The Salem microbarograph showed an abrupt pressure rise amounting to 0.18 in. or 6.1 mb in 1 hr (fig. 9). No thunderstorms accompanied the pseudo cold front at Salem, but one began about 45 min later.

At approximately 1700 PST (fig. 7C), the pseudo cold front also reached Redmond (RDM) east of the Cascades and the southwestern corner of a mesonetwork in the northern Oregon Cascades. Thunderstorm precipitation cells were showing on the Astoria National Weather Service limited-range radar. At 1717 PST, Astoria noted a broken-line echo about 115 mi south-southeast of Astoria with tops estimated to be about 40,000 ft. At 1800 PST, the Seattle, Wash., air traffic control reported radar echoes between Portland and Eugene with tops to 43,000–44,000 ft and commented, "large aircraft being diverted account these thunderstorms." Astoria made additional radar reports at 1810 and 1913 PST (fig. 7E) indicating motion of a line of echoes toward the north at 28 and 25 kt. In 1963, no weather radars or radar meteorologists were operating in the Northwest, or coverage would have been considerably greater.

Between 1700 and 1800 PST, the meso-High in the Willamette Valley attained its highest pressure while the unaffected portions of the heat trough to the north and south were close to their lowest readings, producing a pressure difference of nearly 7 mb in less than 50 mi (fig. 7C, 7D). Some pressure-pattern detail within the mesosystem was derived from microbarograms following the technique of Fujita et al. (1956). The shape, speed, and intensity of the mesosystem were probably more irregular than shown, because of topographic effects and reinforcement by individual thunderstorms.

The pseudo cold front reached Portland a few minutes past 1800 PST accompanied by blowing dust, a thunderstorm, and a fastest mile speed of 53 kt, surpassing the former record for September wind by 20 kt. Similar winds were observed as the system crossed the Mount Hood National Forest in the Cascades, and these will be discussed in detail later. Having developed a mesodepression (Fujita 1963), the squall mesosystem had reached the *mature stage* (fig. 7D).

West of the Cascades, the squall mesosystem continued northward with gradually diminishing intensity. The *dissipating stage*, with the mesodepression at its lowest pressure, was reached shortly after 1900 PST (fig. 7E), and the *remnant stage* was reached soon thereafter as the mesodepression began to fill. The system lost its identity in the Puget Sound area after 2200 PST (fig. 7F). Scattered thunderstorm activity continued west of the Cascades during the night and in western Washington into midmorning of September 10.

Meanwhile, the pseudo cold front seemed to break immediately east of the Cascades, with no well-defined passage noted at The Dalles or Yakima, Wash. Continuity between Redmond and Pendleton, Oreg., to the northeast was much better. Rapidly rising pressure marked the passage at 2050 PST at Pendleton (fig. 9). The squall line passed Walla Walla, Wash., with a thunderstorm an hour later. No evidence of the system could be found by 0100 PST on September 10. An interesting temperature trace was made at Halfway Ranger Station near the Snake

River in northeast Oregon (fig. 8). There, the temperature increased from 62° to 77°F between 2200 and 0000 PST, possibly as a result of squall-line winds blowing downslope off the Wallowa Mountains to the north. It is also possible that the high temperature was a "warm wake" associated with a mesodepression following the meso-High (Staff, NSSP 1963). This is more likely, since a 60°F rise occurred at Meacham, Oreg., a high-level station, between 2030 and 2200 PST.

The squall mesosystem produced different weather in different parts of the State. Along the coast, where higher pressure and cold surface air already prevailed, no surface pseudo cold front was detected, although a distinct line of thunderstorms was tracked by the Astoria radar for several hours as it moved northward over the Coast Ranges. In the northern Willamette Valley, ahead of the marine-push cold air, the system generated striking temperature and pressure contrasts and with these, considerable surface wind. But, despite the system's vigor, it produced very little precipitation at the ground. The principal exceptions were Oakridge, Oreg., about 45 mi Southeast of Eugene, where 0.44 in. of rain fell between 1500 and 1600 PST, and Layng Creek, 15 mi west-southwest of Oakridge, where 0.26 in. fell in the same period.

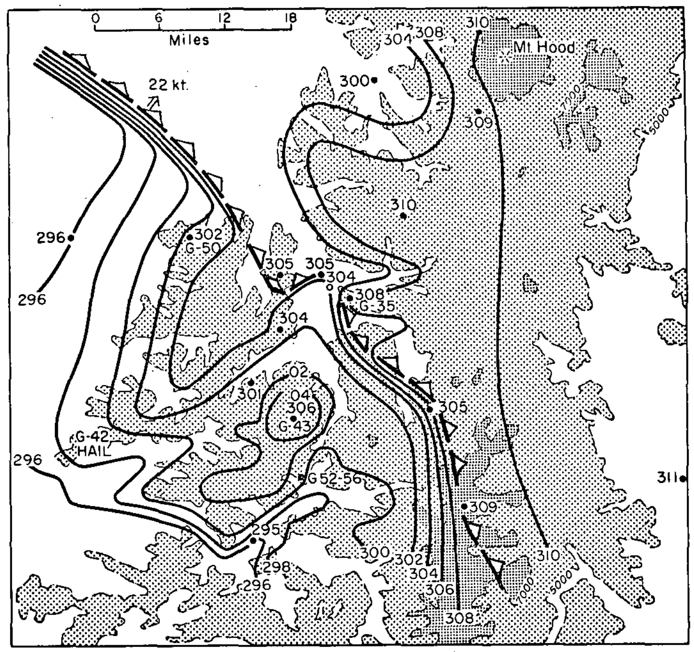

FIGURE 10.—Terrain surface potential temperature (°K) map of pseudo cold front passing through Cascades mesonet at 1800 PST. Reported gusts are indicated in knots.

Passage Through Mesonet

Gale winds accompanied the leading edge of the squall mesosystem as it crossed the Cascade Mountains. Variations from place to place were measured as the pseudo cold front passed through a mesonetwork of 25 lightly instrumented lookout and guard stations in the northern Cascades. For the most part, thunderstorms did not occur until after the front had passed. The effect of a pseudo cold front on surface temperatures is shown by a terrain-surface potential temperature analysis (fig. 10). At 1600 PST, the area was uniformly warm with slightly cooler potential temperatures at lower elevations west of the Cascade Summit. At 1800 PST, the front had moved halfway across the network, accompanied by wind gusts of 35–55 kt and abrupt changes in temperature that depended greatly upon elevation and trajectory of the air (fig. 11). The cold air following the pseudo cold front was markedly stable. At 1,600-ft elevation, Detroit Ranger Station was in particularly cool air that had flowed northeastward behind the front up the North Santiam Valley from the Willamette Valley. The Clackamas River Basin immediately north is surrounded on the east, south, and west by 4,000-ft ridges. Hence, flow into the basin from the south was blocked below 4,000 ft, and air with a potential temperature lower than about 302°K was prevented at chart time from pouring into the basin.

Hygrothermograph traces from 12 mesonet stations showed a variety of pseudo cold-frontal effects on temperature and humidity (fig. 12). Greatest abrupt changes were noted at low-elevation stations outside the mountain area, notably Molalla, Oreg., on the west and Warm Springs on the east. The temperature dropped about 15°F in 10 min at both places. Along the west edge of the Cascades, the peaks were nearly at the top of the cold dome behind the pseudo cold front. This is suggested by the trace at Fish Creek Mountain (5,120 ft), where the temperature actually increased 4°F as the front passed.

No marked event shows on the Bagby Guard Station trace. As is evident in figure 11, air reaching Bagby from any southerly quadrant must descend at least 1,800 ft. The resulting adiabatic warming apparently produced a temperature that, by coincidence, was about equal to the temperature at Bagby before the front passed. And, it did pass there—the forest guard reported sudden winds of 35–40 kt from the southeast. Farther down the valley, at Ripplebrook Ranger Station, the temperature change was more abrupt because the prefrontal potential temperature was about 11½°F higher there than at Bagby.

There was also considerable variation in pressure traces around the area (fig. 13). At Goat Mountain, Oreg., on the west edge of the Cascade Range 4,000 ft above the Willamette Valley, the pressure trace was unsteady, but strangely, there was little evidence of a meso-High despite measured wind gusts to 50 kt from south to west and a temperature drop of 13°F as the pseudo cold front passed. In contrast, Ripplebrook Ranger Station had a pronounced "cold dome" trace, probably due in part to its lower elevation of 1,450 ft. A much broader, though weaker, meso-High is indicated on the trace from Mount Wilson at 5,600 ft on the eastern edge of the range. The pseudo cold front would have undoubtedly been more intense over the the mesonet had it been accompanied by active precipitating thunderstorms. Scattered thunderstorms with gusty winds did occur close to the front and following it over the next few hours, but little rain reached the ground from any of them.

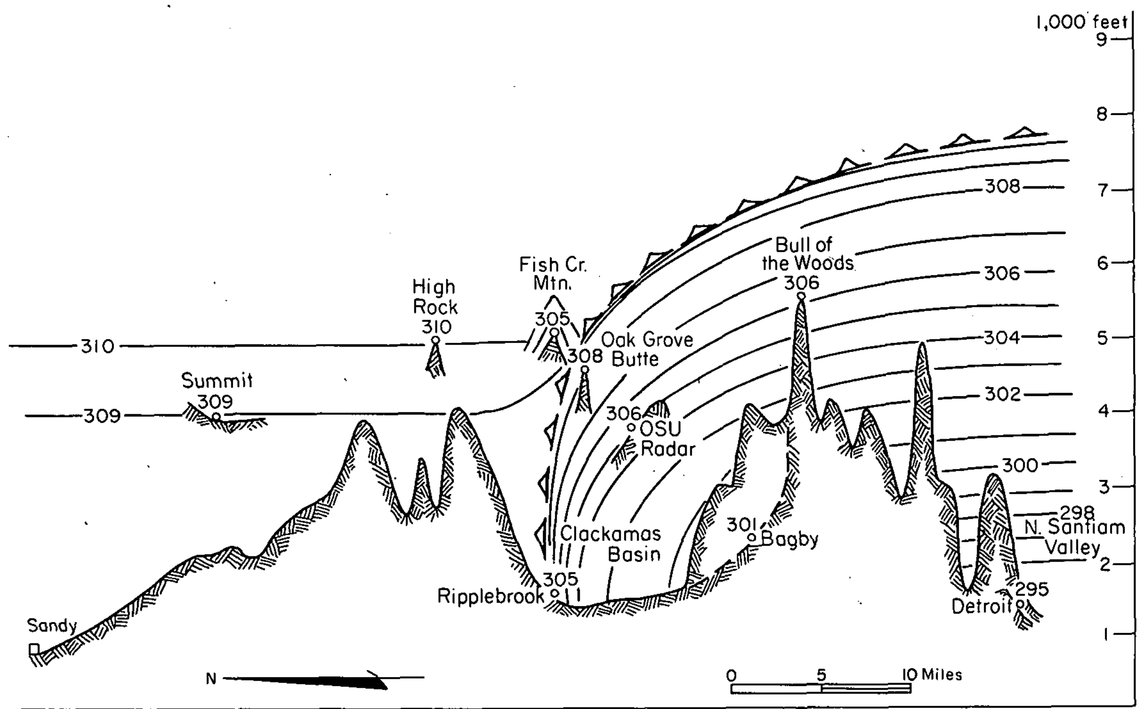

FIGURE 11.—North–south atmospheric cross section of potential temperature (°K) through the mesonet at 1800 PST, Sept. 9, 1963.

The leading edge of the meso-High actually had the striking appearance of a dome. Observers in the area could plainly see the leading surface and apparent dome top near 7,000 ft as the front passed. This height corresponds with the 1,000- to 5,000-ft depths of the cold dome beneath midwest thunderstorms found by Byers and Braham (1949). Observation of the cold dome was possible because the cooler air apparently carried considerable dust and smoke, possibly of Willamette Valley origin, and near the top must have been near saturation. First indication of an impending wind change in the Clackamas River Basin was the appearance of the distinctly smoky air advancing from the southwest corner of the basin.

At the time of the passage, I was on the west slope of Oak Grove Butte at 2,500 ft in the Clackamas Basin. A double-theodolite balloon run had been in progress for only 2 min when the gusty 40-kt south winds hit. The balloon remained in east-southeast winds throughout its 19-min flight but showed increased vertical speed as the front moved underneath. Starting in downslope winds in the lee of Oak Grove Butte, it showed a definite upward component from the 3d to the 11th min, reaching +3.5 m/s from the 4th to 6th min between 4,000 and 7,000 ft. Air rising 2.5 m/s had been noted at the same elevation 1 hr and 43 min earlier. The later flight showed descending air 1 to 1.3 m/s in the 13th and 14th min at 10,000 ft. Horizontal winds for both flights were from around 120° at 6–9 m/s.

A possible lee-slope whirlwind was produced by the pseudo cold front on the lee slope of Oak Grove Butte. It was not observed visually, but a dip appeared in the microbarograph trace at the lookout just as the abrupt pressure rise accompanying the front had begun. An S-type anemometer located 1/4 mi east of the lookout and about 300 ft lower showed southeast winds in excess of 70 kt with gusts to 100 kt during a 15-min period beginning about 10 min after the wind shifted at the lookout. Wind at the lookout averaged SW at 17 kt with gusts to 30 kt during the same interval. Oddly, another anemometer 300 ft uphill showed no wind in excess of 35 kt. Winds from both anemometers were indicated on the same operations recorder strip chart.

Abrupt cooling in the lower layers occurred with the pseudo cold front of the squall mesosystem. The most striking examples are thermograms from Detroit Ranger Station in the Cascades (fig. 12) and Warm Springs east of the Cascades, where 2-hr temperature drops of 17° and 25°F, respectively, were noted. This cool air was of thunderstorm origin and composed the cold dome (Byers and Braham 1949) or meso-High. The cold air was produced by evaporation of precipitation from mesosystem thunderstorms (Fujita 1959). The dry lower layers and high cloud base, variously estimated at 12,000–15,000 ft, were ideal for cold air formation since this is proportional to the amount of precipitation that leaves the cloud and is evaporated before reaching the ground (Newton 1963). This process was effective—although thunderstorms were numerous, except as previously noted, only minor amounts of precipitation were reported. The same evaporation cooling process was responsible for the squall winds accompanying the pseudo cold front (Foster 1958).

7. SYNOPTIC RELATIONS

What, then, were the synoptic scale indications that distinguished September 9 from just another hot day with widespread thunderstorms? All the mesosystems

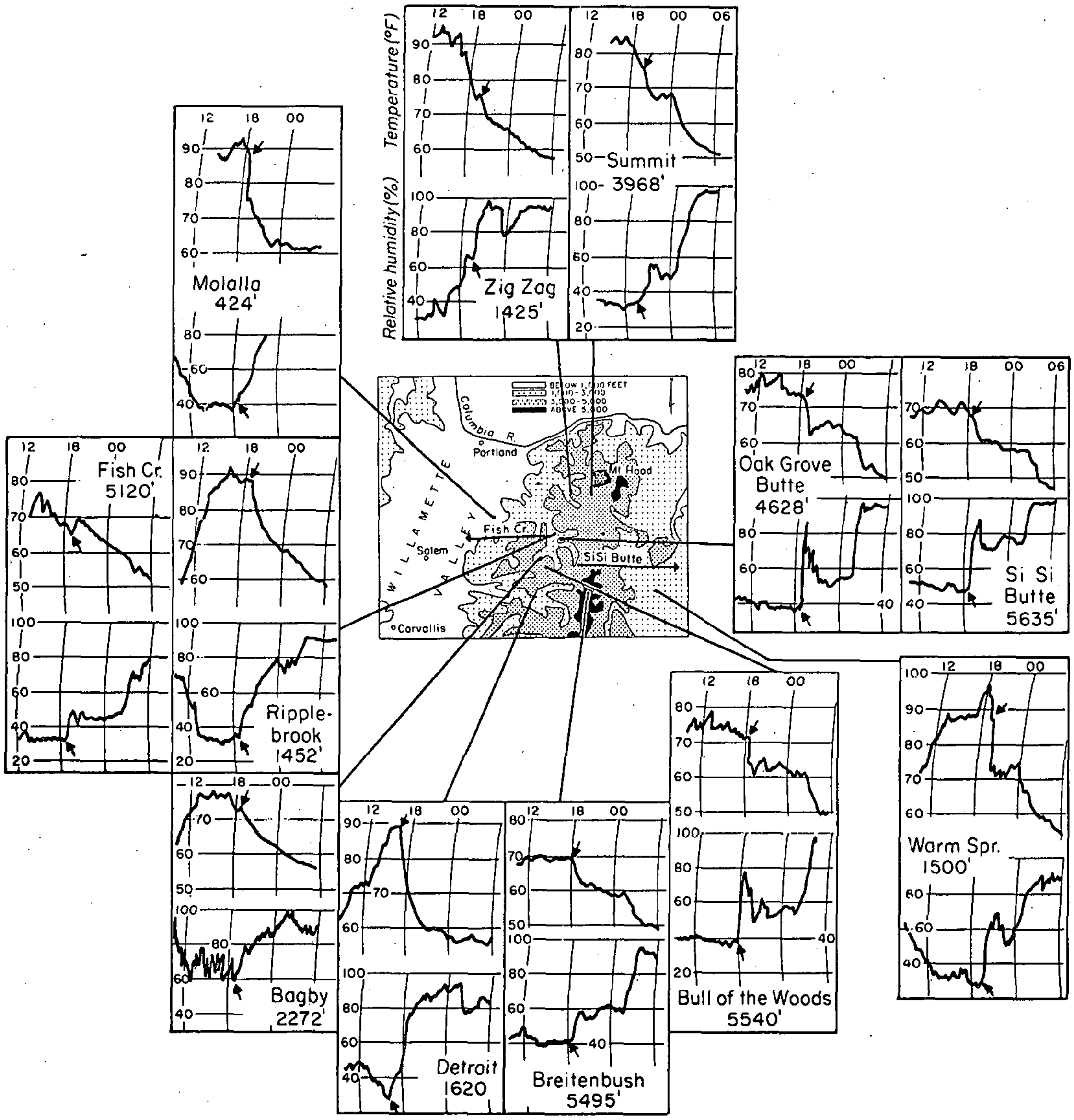

FIGURE 12.—Mesonet hygrothermograph traces in relative positions with pseudo cold-front passages indicated.

of September 9 were probably related to the approach from the south of a minor short-wave trough with a closed circulation at 300 mb that, at 0400 PST on the 9th, was centered some 200 mi west of San Francisco, Calif. (fig. 1). In a study of conditions related to the breakup of western Oregon heat waves, often by a marine push, Graham (1956) found that the sudden influx of marine air was usually related to the passage of a short-wave trough in the westerlies or to a cold Low offshore to the west or southwest. In either configuration, advection of cooler air aloft offshore would tend to further increase surface pressure offshore, an area already under the influence of the east Pacific High. The increase in the onshore pressure gradient at the surface would set the stage for a marine push.

While both squall mesosystems developed from vigorous thunderstorms, the second mesosystem apparently originated near the intersection of the marine-push front and the instability line moving up from the south. The precise beginning of the instability line cannot be pinpointed. Fulks (1951) has pointed out that an instability line may form hundreds of miles in advance of approaching cooler air aloft, and the onshore flow over northern California during the night of September 8 may have been a generating force. The 0400 PST Oakland, Calif., radiosonde observation on the 9th showed the marine layer to be 600 m deeper than 24 hr before. By 1000 PST, Ukiah was 13°F cooler than the preceding day. First evidence of an instability line came with sudden strong south winds when the cool air arrived at Montague at 1300 PST.

It is difficult to establish a clear relationship between succeeding events and upper air changes. There were no marked eccentricities on the upper air maps (700, 500, 300, and 200 mb) at the time of the second squall mesosystem development (fig. 1). The airmass was unstable, and the area was under advection of positive vorticity. The marked difluence in the upper winds over Oregon, north of the maximum winds near the Low, also favored

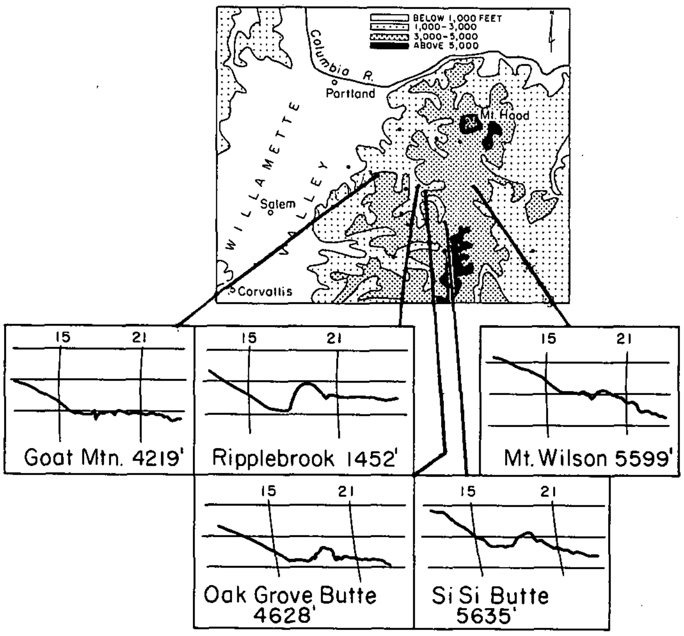

FIGURE 13.—Barograms from the Cascades mesonet for Sept. 9, 1963. Vertical graduations are 0.1 in. of mercury.

severe thunderstorm development. During the time of squall mesosystem formation, the coldest air at the 300-mb level was overhead (fig. 1D); warmer air was being advected at 700 mb (fig. 1F); and this was the time of maximum heating at the ground.

Some decrease in stability due to cooling near the 300-mb level was noted, first at Medford, Oreg., at 0400 PST on the 9th and 12 hr later at Salem. But the most striking changes on both time and space cross sections and upper air charts occurred in the 12-hr period between 1600 PST on the 9th and 0400 PST the next morning (cf. figs. 14A, 14B); that is, after the mesosystems had fully developed. Greatest cooling was at the lower levels (figs. 15A, 15B).

Both Medford and Salem cooled approximately 16°K at 900 mb, presumably with the marine push. At higher levels, cooling resulted from the approach of the cooler central portion of the trough and Low aloft. In another marine push reported by Cramer and Lynott (1970), significant cooling was entirely below 700 mb, with the greatest change (9°K) at about 900 mb.

Because the upper Low moved in from the ocean where it was largely unprobed, we cannot confidently separate, on the morning-after chart, cooling due to the temperature properties of the upper Low from the effects of the marine push, the second squall mesosystem, and extensive thunderstorm activity offshore in the vicinity of the Low during the night. At any rate, marked temperature changes accompanied passage of the minor trough over western Oregon (fig. 14B).

8. CONCLUSIONS

Well-defined mesoevents, including the squall mesosystem and the marine push, do occur in the Pacific Northwest and are responsible for some of the region's most notable summer weather events. Presumably typical of Pacific Northwest squall mesosystems, the two Sept. 9,

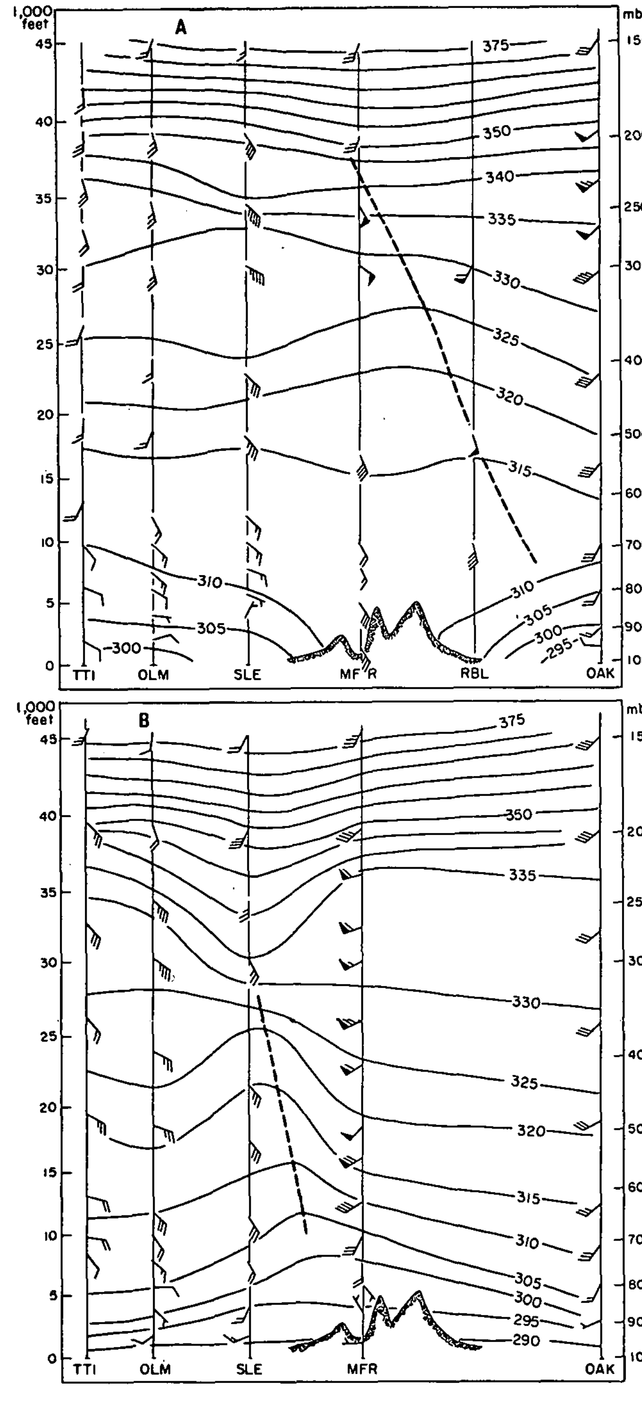

FIGURE 14.—Space cross-sections of potential temperature from Oakland, Calif., to Tatoosh Island, Wash., at (A) 1600 PST, Sept. 9, and (B) 0400 PST, Sept. 10, 1963. The short-wave trough axis is shown by dashed line.

1963, systems were different from the more extensively reported midwestern mesosystems. Moisture was predominantly at high elevations with dry air below; hence, there was little precipitation at the ground. The systems were not related to a cold front as usually defined and were distant from the main jet stream. Jet speed upper winds were present, however, in the vicinity of the minor trough but mostly below the jet stream elevations.

Conditions most conducive to the formation of the squall mesosystems studied are (1) an unstable, moist

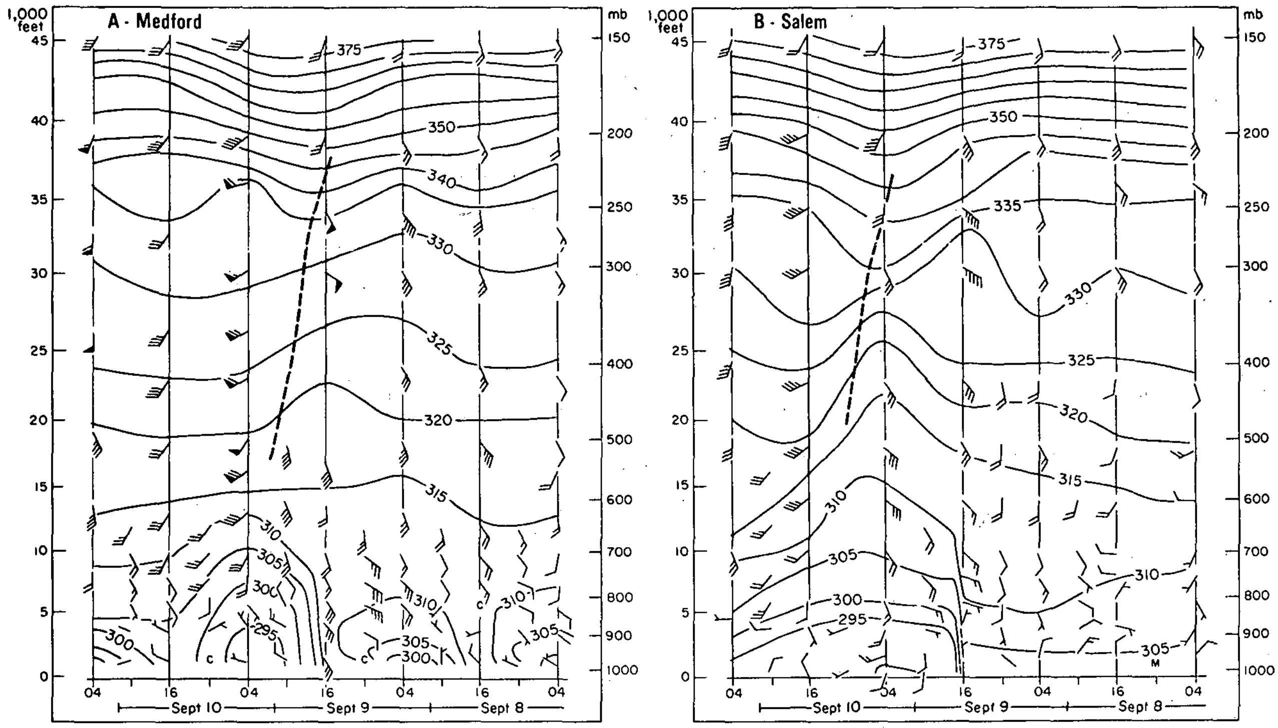

FIGURE 15.—Time cross sections of potential temperature for (A) Medford and (B) Salem, Oreg., for Sept. 8–10, 1963. The short-wave trough axis is shown by dashed line. All times are PST.

air mass already producing scattered thunderstorms and (2) the approach of a short-wave trough with greatest development at 300 mb. The trough in turn produced (1) advection of positive vorticity with increased vertical motion and instability, (2) an area of difluence ahead of jet-force upper level winds, (3) cooler air offshore increasing the lower level onshore flow to marine-push magnitude, thereby providing additional wedge lifting, and (4) an earlier marine push in northern California, which apparently generated the instability line that preceded the squall mesosystem formation.

Forecasters should be alert to the possibilities of abrupt cooling and intensified thunderstorm activity in the Pacific Northwest upon the approach from the south of a minor short-wave trough or remnant of a stagnant upper Low off the California coast.

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